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Transfer length in full-scale pretensioned concrete beams with 1.4 m and 2.4 m section depths

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ABSTRACT

This study aims to investigate the transfer length of full-scale prestressed concrete (PSC) beams with lengths of 30 m and 35 m and section depths of 1.4 m and 2.4 m for highway and railway bridge girders, respectively. To do this, newly developed high-strength (f_{pu} of 2400 MPa) prestressing (PS) strands were used. The initial and effective prestressing forces applied were 94% of the yield strength and 70% of the ultimate tensile strength of the strands. The difference between the transfer lengths at the cut end and dead end was reduced by increasing the section depth. Greater strains were found at the cut end due to a lateral expansion of the strands by the Hoyer effect compared with those at the dead end, causing a greater stress concentration. The eight most widely used prediction models were adopted to predict the transfer lengths of high-strength PS strands in full-scale PSC beams, and it was found that all models significantly overestimated the transfer lengths. Accordingly, the conservative use of the ACI recommendation of $50d_b$ is suggested based on this study.

1. Introduction

In order to increase the span length of concrete structures, prestressing has been frequently adopted. The prestressing construction method can be performed using high-strength prestressing (PS) strands and is classified as a pre-tensioning or post-tensioning method according to the progress sequence of fabrication. For the post-tensioning method, PS strands are inserted into a sheath, which is installed in a mold before concrete casting and pre-tensioned after concrete hardening. The compressive force generated by the pre-tensioned strands is applied to concrete structures based mainly on safely designed prestress anchorage systems. In contrast, for the pre-tensioning method, the PS strands are installed in a mold before concrete casting and pre-tensioned before hardening. Once the cast concrete develops enough initial strength, the strands are detensioned, and a compressive force is then applied to the concrete structures based on the bond performance at the interface between the strands and concrete. Since the interfacial bond performance, which is one of the dominant factors determining the performance of prestressed concrete (PSC) structures, is influenced by several factors, such as concrete strength, magnitude of prestressing force, and shape of strands, the bond performance needs to be thoroughly investigated when new types of PS strands or concrete are developed.

The transfer length is one of the most important bond properties at the interface between strands and concrete, influencing structural design and performance of the pre-tensioning system. The transfer length is defined as the minimum length required to almost completely transferring the effective prestressing force from the PS strands to the surrounding concrete. Because the minimum stress is obtained in concrete by pre-tensioning the PS strands at the end, the transfer length is calculated from the end point to the point where 95% of the convergence point is achieved, based on the 95% average maximum strain (AMS) method [1]. Currently, several international codes [2–4] have suggested different formulas to predict the transfer length of PSC structures considering several parameters, i.e., diameter of the strand, prestressing force, detensioning method, type of the strand, and bond condition. Several researchers [5–8] have tried to improve the accuracy of the prediction models for the transfer length of PSC structures by considering additional parameters, such as the initial concrete strength at release of the strand, cover depth, and unbonded zone, based on their own or previous test data.

In recent years, Oh et al. [8] experimentally and numerically examined the main factors affecting the transfer length of PSC elements using 1860-MPa PS strands. Based on the test data, they concluded that four factors, i.e., effective prestressing force, initial concrete strength at release of the PS strands, diameter of PS strands, and cover depth, have

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the greatest effect on transfer length, and they suggested Eq. (1), as follows:

$$l_t = 8\sqrt{f_{pe}}\left(\frac{1}{f'_{ci}}\right)^{1/3} d_b^{1.28}\left(\frac{1}{c-20} + 0.25\right) \tag{1}$$

where l_t is the transfer length, f_{pe} is the effective prestressing stress in the strand after loss, d_b is the nominal diameter of the strand, and c is the concrete cover depth.

Even though Eq. (1) was proposed based on test data using a sudden release method, it could predict the transfer length more precisely than other formulas from the previous international codes and researchers since it considered various parameters [9]. Kim et al. [10] first experimentally evaluated the transfer length of PSC elements using high-strength (f_{pu} of 2400 MPa) PS strands, newly fabricated in Korea. Various factors, such as compressive strength of concrete, tensile strength of PS strands (f_{pu} of 1860 MPa vs. f_{pu} of 2400 MPa), existence of steel fibers, and number of stirrups, were considered to evaluate the effects of those factors on transfer length. Most importantly, they concluded that the use of 30% higher strength PS strands results in increased transfer length compared to its counterpart, and the difference between the transfer lengths of the cut end and dead end (sudden release vs. gradual release) becomes more obvious when a higher strength PS strand is applied. Even though the characteristics of the transfer length of the high-strength PS strand were evaluated by Kim et al. [10], extending their results to full-scale structures is limited. This extension is necessary because the transfer length is strongly influenced by the amount of concrete above the strands [11], which may significantly affect the results. Therefore, in order to practically use such a newly developed high-strength PS strand, its transfer length needs to be evaluated using full-scale structures, and the applicability of the prediction models given by current codes and previous researchers requires examination.

Accordingly, this study examined the transfer length of a high-strength 2400-MPa PS strand using two different full-scale PSC girders with section depths of 1.4 m and 2.4 m, respectively. To the Author's knowledge, the experimental campaign reported in the following is the world's first investigation on the topic. The implications of the detensioning method and size effect on the transfer length were also estimated. Lastly, for its practical application, the measured transfer lengths were compared with the eight most widely used prediction models, and their applicability was evaluated.

2. Experimental program

2.1. Details of test specimens and measurement

Normally, PS strands are installed all over the bottom flange section and the length of pretensioned PSC beams in order to assure sufficient strength and serviceability of structures. In contrast, the pretensioned PSC beams used in this test are parts of segmented beams, which will be connected later by post-tensioning, so pre-tensioning was applied to only part of the member. As shown in Figs. 1 and 2, two different types of PSC beams (i.e., Beam A and Beam B), designed for a 30-m long highway bridge girder and a 35-m long railway bridge girder, respectively, were fabricated. Beam A had a height of 1.4 m and width of 0.8 m and contained two and six strands in the top and bottom flanges, respectively (Fig. 1). It has hollow at the center of cross-section, and the thicknesses of walls and above flange were both 200 mm. Beam B had a height of 2.4 m and width of 1.0 m and included six strands in the bottom flange only, as shown in Fig. 2. For Beam A, the horizontal and vertical spacing of the strands was 100 mm and 65 mm, respectively, while the horizontal spacing of the strands for Beam B was 55 mm. The cover depths of the strands to the concrete surface of Beam A were 84.8 mm for strands #1 and #2, 77.4 mm for strands #3 and #4, and 57.4 mm for strands #5, #6, #7, and #8. For Beam B, an identical cover depth of the strands to the concrete surface of 100 mm was applied for all strands.

Pretension was obtained by applying a 266 kN load, which is 94% of the yield strength of the strand, $0.94f_y$, to each strand, as shown in Fig. 3. Herein, f_y is the yield strength of the prestressing strand. Load cells and strain gages were installed for strands #2, #5 and #8 and strands #1, #2, #4, #6, #7, and #8, respectively, for measuring the stress loss of Beam A when the prestressing load was applied through a wedge, as shown in Figs. 4a and 5. In addition, load cells and strain gages were applied to all strands (#1–#6) of Beam B to measure the stress loss, as given in Fig. 5. The measured stress loss was approximately 34.2 kN on average. The prestressing force, which is actually developed in each strand for both Beams A and B after stress loss and releasing all strands, was thus found to be 231.8 kN on average, which is approximately 70% of the tensile strength of the strand, $0.70f_{pu}$, where f_{pu} is the ultimate tensile strength of the strand.

To measure the transfer length, electric resistance strain gages were attached to two bottom longitudinal rebars, which are indicated by two arrows in Figs. 1 and 2. The picture for the attached strain gauges is also given in Fig. 4. For the Beam A, D10 steel rebars having a nominal diameter of 9.53 mm, nominal area of 71.3 mm^2, yield strength of 400 MPa, and ultimate tensile strength of 560 MPa were used, while D16 steel rebars with a nominal diameter of 15.9 mm, nominal area of 198.6 mm^2, yield strength of 400 MPa, and ultimate tensile strength of 560 MPa was adopted for the Beam B. The surface of ribs in the steel bars was eliminated by using a diamond grinder at the point where strain gauges were attached, and the strain gauges were tightly bonded to the steel rebar using a superglue. Then, they were covered with waterproof and insulating tape and the lead wire was covered with very thin plastic pipe to prevent failure during concrete casting and cutting the stands. In the case of small sized specimens for measuring the transfer length, in general, they do not have rebars, so Demec (Demountable mechanical) or electric resistance strain gages are attached to the concrete surface, and the transfer length is obtained by measuring them. As the transfer length is a result of interaction between strand and surrounding concrete, the measurement of strains in concrete would be appropriate for estimation of the transfer lengths of strands. However, in this study, to obtain stable data and eliminate some measurement errors due to poor installation of Demec point, strain meter reading errors, and poor concrete surface conditions, strains of adjacent steel rebars were alternatively used for indirect measurements of concrete strain. Since the specimens are full-scale and have steel rebars installed near strands and running parallel to the strands, electric resistance strain gages were attached to flexural rebars with a spacing of 100 mm starting 70 mm from the beam end to 1170 mm and with a 3750-mm spacing in the center of beam. A total of 50 strain gages were attached for each Beam A and Beam B. A total of 22 gages were installed at each beam end, and three gages were installed at the beam center and 3.75 m distance from the center at both sides for each set of two rebars. The prestress was released by a sudden release method (i.e., flame cutting) using an oxygen welding machine at the cut end, as shown in Fig. 6a. Due to such a sudden release of prestressing force at the cut end, the strands were untwisted after complete of releasing all strands at near the beam end, as shown in Fig. 6b. Since most of the prestressing forces was released immediately after cutting the strands at the cut end, the strands at the dead end were relatively gradually released although the identical oxygen welding machine was used. Thus, it is denoted as a gradual release of the prestressing force at the dead end. The beam end with gages C1–C22 installed was the cut end, and the other end with gages G1–G22 installed was the dead end for both Beams A and B. If bond failure or large slip between the rebar and concrete are generated, the steel strains cannot be used as adjacent concrete strains. Therefore, the maximum bar stress was checked carefully to determine whether bond failure occurred.

As we release the pre-tensioned strands, compressive force is activated immediately, causing a generation of compressive strains in the